NEXT-GENERATION ELECTROMAGNETIC SOUNDING OF THE LUNAR INTERIOR. R. E. Grimm[1] and G.T. Delory[2], [1]Department of Space Studies, Southwest Research Institute, 1050 Walnut St. #300, Boulder, CO 80302 (grimm@boulder.swri.edu), [2]Space Sciences Laboratory, University of California, Berkeley, CA 94720 (gdelory@ssl.berkeley.edu).

Introduction. Electromagnetic (EM) sounding of the Moon has placed upper limits on core size, determined the abundance of free iron in the upper mantle, and constrained the mantle temperature structure and global thermal evolution [e.g., 1-7]. The next generation of EM measurements can focus on shorter signal periods in order to probe the nature of the upper mantle and crust. Introduction of the magnetotelluric (MT) method to lunar studies would enable natural-source soundings from a single station—without an adjoint orbiter—using simultaneous measurements of the electric and magnetic fields. Special attention to plasma effects is necessary. A network of MT surface stations is useful for investigating lateral heterogeneity but each sounding is independent.

Lunar EM Sounding. Time-varying EM source fields induce eddy currents in planetary interiors, whose secondary EM fields are detected at the surface. These secondary fields shield the deeper interior according to the skin-depth effect, so that EM fields fall to 1/e amplitude over depth δ (km) $= 0.5\sqrt{\rho/f}$, where ρ is the resistivity and f is the frequency. EM sounding methods exploit the skin-depth effect by using measurements over a range of frequency to reconstruct resistivity over a range of depth [8,9] (time-domain soundings have theoretical equivalents in the frequency domain although there are practical differences).

The tested approach to lunar sounding is the *transfer-function method*, which independently measures the source and source+induced magnetic (B) fields from a satellite and a surface station, respectively [3,5]. The secondary field is assumed to arise from unipolar induction of a layered sphere so that only the temporal correlation between the satellite and surface is used. In the limiting case where only the size of a highly conductive core is sought, the secondary field is assumed to be purely dipolar and the requirement is reduced to one set of measurements from an orbiter, as was performed using Lunar Prospector [6].

While the full potential of existing data has not been reached, new fundamental insights into the lunar interior will require new measurements. A summary plot of lunar conductivity vs. depth (Fig. 1, top) shows significant uncertainty at both extrema in radius. The highly conducting core appears to have confined eddy currents to its surface at the periods tested so far (<55 hr, [4]). It may be possible to distinguish a molten silicate core from an iron core at longer periods (hundreds of hours) but it is unclear if useful long-period natural signals exist. A global seismic network is the best approach to resolving the core question.

Conversely, the crust and upper mantle have been poorly resolved (Fig. 1) because very high resistivities in the cold outer portions of the Moon are still associated with large skin depths even at the highest useful frequency in the current data sets (~10 mHz). The frequency band must be extended well beyond this limit in order to accurately probe the outermost few hundred kilometers of the Moon (Fig. 2, bottom). For example, characterizing the region that may represent the solidified magma ocean at depths of a few hundred kilometers calls for frequencies 0.1-1 Hz, and frequencies of 100 Hz or more may be required to detect any EM signature of the crust-mantle boundary. The outermost several hundred kilometers are therefore new frontier for lunar EM sounding. As frequency is increased, however, spatial aliasing invalidates the transfer-function methods, requiring alternative approaches.

Wide World of Electromagnetics. The fundamental quantity that must be derived in any sounding is the frequency-dependent EM impedance Z, and it is the variety of approaches to Z that lead to more individual techniques in EM than in any other geophysical method [8,9]. The impedance is related to the apparent resistivity ρ_a—the most commonly used parameter beause of its dimensional analog to true resistivity—as $\rho_a = Z^2/\mu\omega$, where μ is the permittivity and ω is the angular frequency.

Two classic EM methods may be suited to next-generation lunar sounding. The first, *geomagnetic depth sounding* (GDS), forms the impedance from the ratio of B_z, the vertical magnetic field to $|\nabla B_h|$ the magnitude of the horizontal magnetic-field gradient, as $Z = \mu\omega B_z/|\nabla B_h|$ [10]. Because the wavelength in the ground $\lambda = 2\pi\delta$, GDS arrays require station spacings comparable to the skin depth in order to resolve the relevant horizontal wave structure. Therefore a globally distributed magnetometer network on the Moon will only resolve deep structure, for instance, to probe a molten silicate core or to constrain the size of an iron core. If, however, regional arrays with station separations of tens to hundreds of kilometers are emplaced, then local soundings can be done of the poorly resolved upper mantle.

The second approach to be considered offers complete shallow-to-deep sounding from a single station. Single-station methods are also best for investigating lateral heterogeneity, e.g., differences between PKT, SPA, and FHT [11]. The *magnetotelluric method*

(MT) uses orthogonal horizontal components of the electric (E) and magnetic (B) fields to form $Z = \mu|E/B|$ [12]. MT has vastly outpaced GDS in terrestrial exploration in recent decades because of its simplicity. Arrays are widely used, but only to provide more rapid geographic coverage and internal cross-checks among stations (remote reference).

Broad Spectrum Available. Terrestrial MT utilizes the vast array of naturally occurring atmospheric electrical activity and waves generated by magnetosphere-solar wind interactions as sounding sources. Like the Earth, the active lunar plasma environment will also contain a multitude of electromagnetic and hydromagnetic waves useful for MT, where the presence of magnetic anomalies, shocks, and the lunar wake will provide instabilities conducive to wave generation. Measurements by Lunar Prospector confirm the presence of whistler modes between 0.4-4 Hz on the dayside, often associated with the magnetic anomalies, [**Fig.2**, ref. 13], while Geotail has measured ULF waves in the lunar wake [14]. At higher frequencies, electromagnetic modes at multiples of the electron plasma frequency have been observed both inside and outside the wake [15]. In general, broadband wave activity up to at least several hundred Hz is expected on and around the Moon, as in other similar environments such as planetary bow shocks [e.g., 16].

Decades of experience in the measurement of electric fields in the magnetosphere and the solar wind demonstrates the feasibility of measuring horizontal electric fields on the lunar surface. For the purposes of MT, attention to the measured wave modes will be important in order to distinguish electrostatic from electromagnetic emissions, and also characterize the propagation geometry of EM modes relative to the surface and the solar wind magnetic field. This may require auxiliary measurement of plasma properties (Langmuir probe) and/or the vertical E-field.

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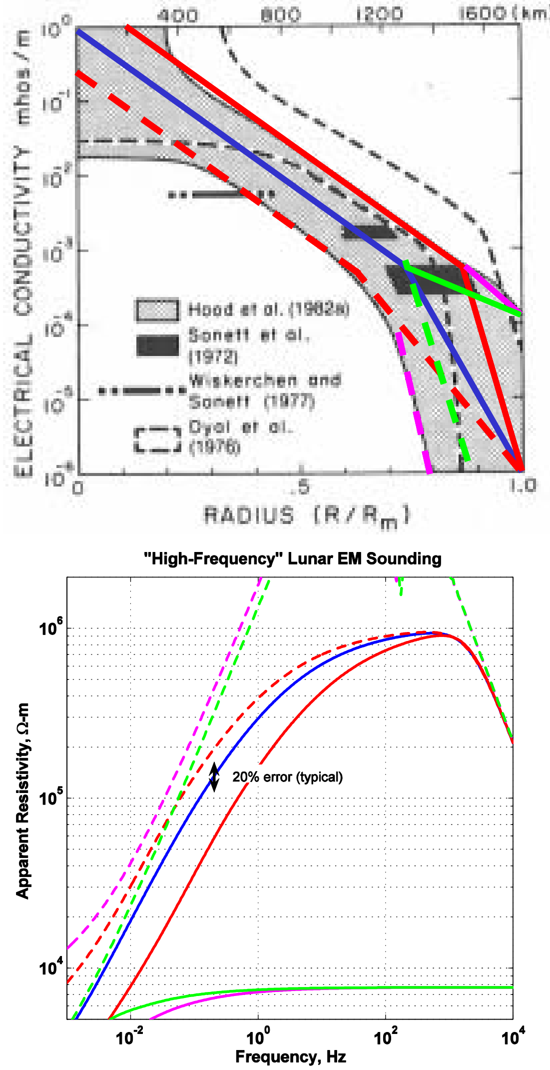

Figure 1. *Top*: Lunar conductivity structure derived from Apollo/Explorer [4]. Note large uncertainties in shallow and deep structure. *Bottom*: 1D models of EM response from 1 mHz – 10 kHz. Major uncertainties in mid- and upper-mantle conductivities are resolved in the band ~10 mHz to 10 Hz.

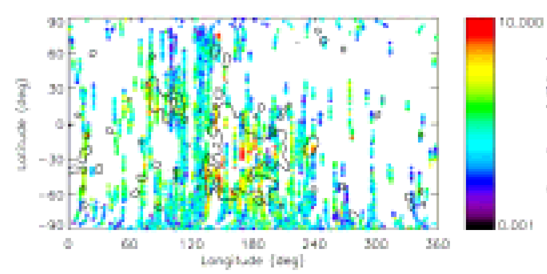

Figure 2: Distribution of coherent, monochromatic whistler-mode waves measured by Lunar Prospector [13].